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Research Article

Temperature dynamics in crevasse-drainage systems of Antarctic glaciers

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Abstract

During the 33rd Bulgarian Antarctic Expedition, field studies were conducted to examine the internal microclimate of crevasse-drainage systems of the three glaciers: Balkan Ice Field, Johnsons and Contell Glaciers. The research is focusing on the relationship between fluctuations of surface meteorology parameters, internal air glacier temperatures in the crevasses and possible connection with solar activity. The total duration of the study exceeds 60 days, making it the longest temperature monitoring of glacier crevasses in Antarctica. Measurements of air temperature, humidity, and atmospheric pressure were carried out using autonomous sensors, while ultrasonic anemometers recorded airflow direction and speed inside the crevasses. Sensors were placed at depths of up to 25 m in central zones and 10 m near the glacier edges. The study identified a distinct temperature gradient at 3-meter intervals and mapped the depth of zones with persistently negative temperatures. Increased solar activity was associated with lower internal glacier temperatures and stronger air circulation. A negative correlation was found between solar activity and both temperature and downward airflow within crevasses. A glacial cave under the Balkan Ice Field allowed access to subglacial waters and sediment sampling. For the period of one year, the ablation zone of the Balkan Ice Field had expanded, and the constant negative temperature zone had deepened by 6–7 m since the previous expedition. Contell Glacier showed greater thermal stability and resistance to change compared to the larger ice fields. The extended daylight in January (approximately 20 hours) facilitated reliable correlation with solar activity patterns.

Key words: Antarctic climate anomaly, airflow dynamics, Balkan Ice Field, Contell Glacier, cosmic rays, Johnsons Glacier, sunspots, thermal gradient

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1. Introduction

The Intergovernmental Panel on Climate Change (IPCC) (Calvin et al. 2023) released its Sixth Assessment Report (AR6) between 2021 and 2023, providing a comprehensive overview of the current state of climate science, confirms that human activities, particularly greenhouse gas emissions, have unequivocally caused global warming. It notes that the global surface temperature has increased by approximately 1.1°C above pre-industrial levels (1850–1900) during the period 2011–2020. The report also highlights the increased frequency and intensity of extreme weather events, such as heatwaves, heavy precipitation, and droughts, as a result of climate change. Bracegirdle et al. (2024) present the first comprehensive analysis of the impact of climate change on seasonal extremes in Antarctica. Their analysis shows that winter cold extremes are decreasing, particularly in regions with sea ice, as a result of warming and sea-ice retreat. Summer extremes (heavy precipitation and strong winds) are increasing, especially in affected regions such as the Antarctic Peninsula, driven by changes in the ozone layer and the circumpolar westerly jet. The underlying mechanisms include sea-ice retreat and transformations in atmospheric circulation (the jet and storm tracks).

In the IPCC report Climate Change 2001, the relationship between Southern Ocean temperatures and ice shelf melting remains uncertain. The circulation of meltwater beneath ice shelves is complex. According to (The IMBIE Team 2018). The loss of ice from Antarctica has tripled—from an average of 76 Gt/year to 219 Gt/year in the period after 2012, reflecting an accelerated trend in mass loss and contribution to sea level rise. Any increase in melting due to climate warming leads to the formation of a fresher, less saline layer of water (Jacobs et al. 1992; O'Farrell et al. 1997), which acts as an insulator and may inhibit further melting. Based on a three-dimensional model adapted to the underside of the Amery Ice Shelf, Williams et al. (1998) conclude that when adjacent seas were warmed by 1°C, net melting increased more than three times. Recent studies demonstrate that reduced sea ice formation enhances salinity-driven circulation changes, thereby accelerating upper ocean currents on the Antarctic shelf (Dawson et al. 2025).

Continental glaciation is characteristic of polar regions such as Antarctica and Greenland. The ice forms vast ice fields over 3 km thick, which flow toward the coastal areas. All glaciers have two distinct zones: the head, where the snow accumulates, modifies its state and begins to slide (accumulation zone), and the front, at the end of the tongue, where the ice turns into water (ablation zone). The shape of the glaciers is closely correlated to the morphology of the landscape, which is slowly altered by the glaciers themselves. They are also affected by the changing meteorological conditions, not as promptly as rivers, but still in a relatively short time, years or decades.

Crevasses form when the stress generated by glacier dynamics exceeds the mechanical strength of the ice. Typically, brittle failure occurs under tensile stress, producing fractures oriented perpendicular to the direction of ice flow. However, failure can also result from shear stress, leading to the formation of crevasses aligned parallel to the flow direction. Colgan et. al. (2016) describe that crevasses are not merely a consequence of glacier dynamics, but also an active factor influencing changes in glacier mass. Advances in satellite observation and algorithm development now allow for the automatic detection and monitoring of crevasse evolution. Laser and radar altimetry enhance data acquisition in remote and hard-to-access regions.

Crevasses in glaciers act as natural insulators, shielded from short-term atmospheric fluctuations. This makes them well-suited for recording the thermal response of the glacier to external influences such as solar radiation. Investigating the potential relationship between variations in solar activity and the temperature gradient within crevasses of Antarctic glaciers, particularly at latitudes corresponding to the outer boundary of Antarctica, contributes to more accurate modeling of future climate scenarios and enables the detection of resonance effects between external drivers, such as solar and glaciological factors.

The outer boundary of Antarctica (Antarctic Convergence) is the first to register global climate shifts, and studies in this region will help distinguish between climate changes driven by anthropogenic influences and those arising from purely natural cycles. The Antarctic Convergence is a natural oceanic boundary where cold Antarctic waters meet the relatively warmer and saltier sub-Antarctic waters. These two water masses differ markedly in temperature, salinity, and density. The proximity of the South Shetland Islands to the outer boundaries of Antarctica makes them a suitable location for monitoring the rate of ongoing climate change. The permanent ice cover of South Shetland Islands' Livingston Island and the neighboring islands of Greenwich, Robert, and Snow in Antarctica has decreased by 16% since 1956 (Soffiatti et al. 2024). Newly ice-free areas absorb more solar radiation, and the thermal inertia of exposed rock surfaces leads to the retention of greater amounts of heat.

The differences in the morphology of various types of glaciers—Alpine glaciers, as described by Oerlemans (2001), and continental glaciers (Rignot et al. 2011) determine the different processes through which they lose mass. Alpine glaciers, typically found in mountainous regions, are more sensitive to atmospheric temperature changes and often lose mass through surface melting and runoff. In contrast, continental glaciers, such as those in Antarctica, primarily lose mass through basal melting and calving at the ice front, processes influenced by oceanic conditions.

The work of Berg and Bassis (2022) contributes to a growing body of research emphasizing that internal glacier processes, such as crevasse formation and advection, play a critical role in glacier stability and their response to a warming climate.

The Balkan Ice Field on Livingston Island includes the Perunika and Contell Glaciers, while the Hurd Ice Field includes the Johnsons Glacier. While alpine type glaciers, such as Contell and Johnsons have shapes dictated by the terrain, most continental glaciers can spread over vast areas without clear boundaries. The internal temperatures of glaciers depend on the balance between solar radiation, heat transfer through the atmosphere, and thermal processes within the ice. Changes in solar activity associated with the solar cycle (~11 years) can lead to periods of warming or cooling that influence the glacier mass balance. It has been suggested that galactic cosmic rays could impact Earth's climate by influencing cloud formation. If variations in cloud cover contribute to climate change, their effect in Antarctica differs from the rest of the world. Using satellite data from the Earth Radiation Budget Experiment (ERBE), this study calculates how small percentage changes in cloudiness affect surface temperatures across all latitudes (Ramanathan et al. 1989). The findings align with observed temperature differences both globally and in Antarctica. This suggests that clouds are not merely passive responders to climate shifts but actively contribute to climate forcing, influenced by changes in the solar magnetic field that regulate cosmic-ray flux (Svensmark 2006). We use the conclusions about the effect of solar activity changes on clouds to explain our results.

Studies of the thermodynamics of air masses within glaciers can provide insight into the relationship between solar activity and subglacial temperatures. Historically, the thermodynamics of crevasses in an Alpine glacier in New Zealand have been studied using temperature sensors (Purdie et al. 2023). Morphological studies of subglacial drainage cavities in Antarctica have been conducted using radar (Schaap et al. 2020). Only a few studies have looked at how changes in solar activity might affect stable temperatures in underground spaces (Stoev and Stoeva 2021). The glacier's location near the edge of Antarctica makes it particularly vulnerable to the effects of climate change and variations in solar activity. This positioning enhances its relevance as a case study site. Similar research on mountain glaciers situated near climatic boundaries has been carried out globally, including studies by Gachev (2021) and Gachev et al. (2024). Research has also been conducted on the calculation of glacial hydrological potential, glacier melt rates, and the estimation of outflowing water streams in Antarctica (Willis et al. 2016). The dynamics and seismic activity of glaciers surrounding the Spanish Antarctic base Juan Carlos I on Livingston Island and the Bulgarian base St. Kliment Ohridski have been studied by Martín et al. (2004), Georgieva et al. (2019) and Letamendia et al. (2023).

Studies of temperature within glacier crevasses have been conducted primarily on mountain glaciers and in Greenland. Despite numerous studies, the effect of changes in solar activity on air temperatures within glaciers in Antarctica remains poorly understood. This study aims to investigate heat exchange processes between the near-surface atmospheric layer and glacier crevasses in Antarctica, as well as the temperature gradient and directions of airflow under changes of solar activity by addressing the following research objectives:

1. Determining the temperature gradient in the crevasses of the Contell, Johnsons, and Balkan Glaciers.
2. Identifying the direction and magnitude of airflows within drainage systems.
3. Measuring the change in depth of the zone with permanently negative temperatures over one year.
4. Calculating the correlation between external temperature parameters, solar activity, and meteorological parameters in the crevasse-drainage systems.
5. Reaching the bottom of the glacier to measure the temperature of water flows under the ice.

2. Data and methods

2.1. Case study area

The case study area is located on Hurd Peninsula on Livingston Island (Fig. 1C), which is part of the South Shetland Islands archipelago in Antarctica (Fig. 1A). The studied glaciers are Balkan Ice Field, Contell Glacier, and Johnsons Glacier (Fig. 1D).

2.1.1. Balkan Ice Field

Balkan Ice Field is an ice-covered plateau located in eastern Livingston Island, part of the South Shetland Islands in Antarctica. Its elevation varies between 150 to 280 m. The snowfield lies south of the lower Perunika Glacier, northwest of the Huntress Glacier, and north of the Contell Glacier. It spans 3 km in length from southwest to northeast and 2 km in width. It is bordered by Burdick Ridge to the east, Willan Nunatak and Castillo Nunatak to the southeast, and Krum Rock to the southwest. The snowfield has a gentle northwestward slope, with its base bordered by hills along Bulgarian Beach. The Balkan Ice Field, including the Perunika and Contell Glaciers and the Hurd Ice Field, including the Glacier Johnsons.

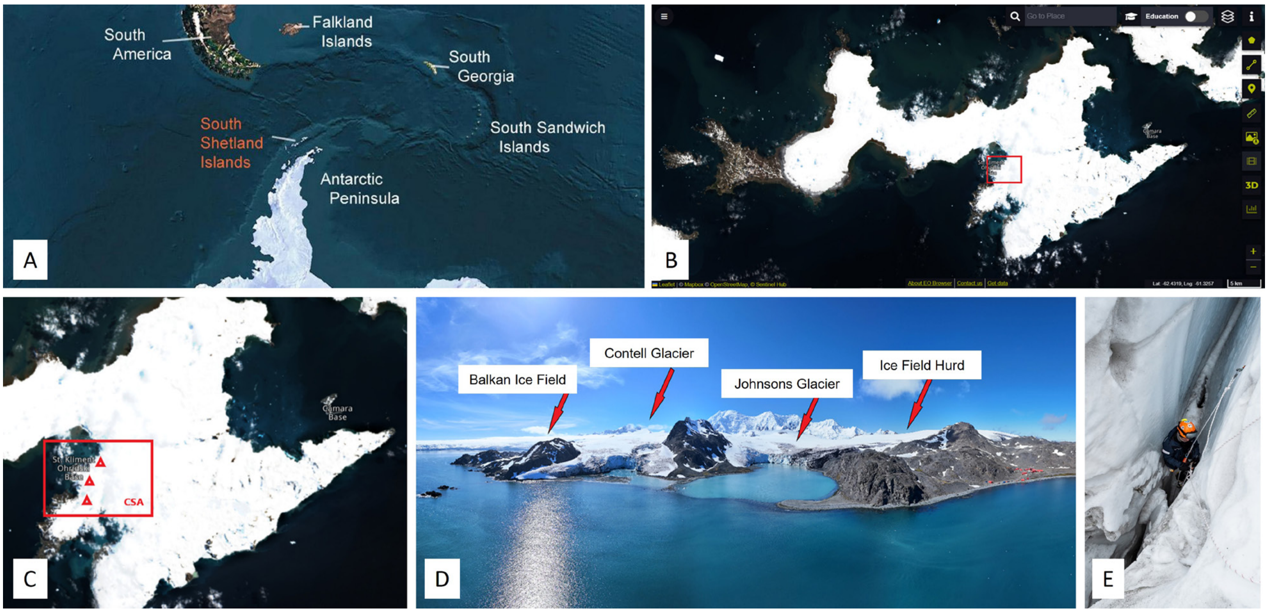

Figure 1. Case study area **A** location of South Shetland Islands **B** overview of Livingston Island **C** closer look of the Livingston Island with the three glaciers **D** location of the glaciers Balkan, Contell and Johnsons **E** installation of sensors in Contell Glacier.

Between December 29, 2024, and February 15, 2025, a total of 19 sensors for measuring temperature and relative humidity were deployed on a rotational basis across the studied glaciers. All sensors were configured to record temperature every 30 minutes.

2.1.2. Contell Glacier

Fig.1D is a 2 km long and 0.74 km wide glacier on Hurd Peninsula, Livingston Island in the South Shetland Islands, Antarctica, bounded by Atlantic Club Ridge to the northwest, Krum Rock to the north, Balkan Ice Field to the northeast, and Charrua Ridge and Charrúa Gap to the south. It is crescent-shaped, running northwestwards in its upper course, then between Charrúa Ridge and Krum Rock, turning west-southwestwards to flow into South Bay north of Johnsons Dock.

In a crevasse located at the boundary between the accumulation zone and the ablation zone of the Contell Glacier (Fig. 5), three sensors for measuring and recording temperature and relative humidity were installed from 6th of January 2025, to 4th of February 2025. The reached depth was -11 m.

2.1.3. Johnsons Glacier

Fig.1D is the 1.8 km long and 2.3 km wide glacier on Hurd Peninsula, Livingston Island, bounded by Charrúa Ridge and Charrúa Gap to the north, Napier Peak to the east, Mirador Hill to the southeast, Hurd Ice Cap (from which it receives ice influx) to the southwest and Mount Reina Sofía to the west. It is draining northwestwards into Johnsons Dock. The glacier provides overland access from the Spanish base Juan Carlos Primero to the interior of the eastern Livingston Island.

2.2. Organization of field measurements

2.2.1. Sensors on site

For the measurements inside the crevasses, we used the data loggers TGP-4500 (Fig. 2A). They monitor temperatures from -25 to +85°C, and relative humidity (RH) from 0 to 100% using built-in sensors. The sensor's accuracy is ±0.02°C. The coated RH sensor offers good resistance to moisture and condensation, and like the rest of the Plus 2 range, this accurate and reliable unit is ideal for monitoring in outdoor applications.

Figure 2. Sensors on site **A** and **B** sensors for air temperatures in crevasses of Johnsons Glacier **C** outside meteo data loggers Comet U4130.

2.2.2. Surface meteorology

The determination of a statistically significant relationship between sunspots and the outside air temperature in field conditions on the glaciers could not be achieved. The problem lies in the fact that all meteorological stations on Livingston Island are mounted on rock foundations, which during the summer season and long daylight of 17–18 hours, absorb large amounts of ultraviolet radiation from the sun, and due to the high thermal inertia of the rocks, the measurements are subject to large errors. The attempt to place loggers on the glacier ice surface also failed for the same reason, as within a few hours, the sensors and their stands "sank" about 10 cm into the ice and became covered with water. For a reliable measurement of outside air temperature, we have considered the uppermost sensors installed in the crevasses, located between 3 and 6 m below the glacier surface.

In addition to the sensors placed in the glacial cracks, two autonomous sensors, COMET U4130, were installed near the surface of the glacier to measure and record the external temperature, humidity, dew point, and atmospheric pressure. These same sensors were used for two years to study the relationship between surface atmospheric parameters (Parov 2023) and temperature changes in the underground volumes of the deepest karst cave in Bulgaria.

The data around the glacier were recorded every 30 minutes, with the sensors' clocks being pre-synchronized. Additionally, every day, the measurements were compared with the meteorological station Meteorocks (Fig. 3) above the St. Kliment Ohridski Base: 62°38'29" S, 60°21'53" W, which described the weather conditions and wind measurements.

Figure 3. Hardware of the meteo-station Metheorocks.

2.2.3. Wind speed and direction into the crevasse

At the beginning of the study, we placed two ultrasonic anemometers Gill WindSonic M (Fig. 4) at a depth of 6 m in the glacial crack (C2) and (C4) (Fig. 5) on the Balkan Ice Field and Johnsons Glacier (JD1) to measure the direction and amount of air flow.

After one week of measurements, the first anemometer was moved to (C6), which is closer to the end of the glacier. The measurements and recording were done every minute. The manufacturer Gill Instruments Ltd, confirmed that the devices can operate when tilted. The position of the anemometer was tilted sideways, with the arrow, which normally points north, directed upward in this case. This allowed us to classify all air flows with an angle smaller than 90° and larger than 270° as “Downward movement”. Conversely, air flows with an angle larger than 90° and smaller than 270° were classified as “Upward movement”.

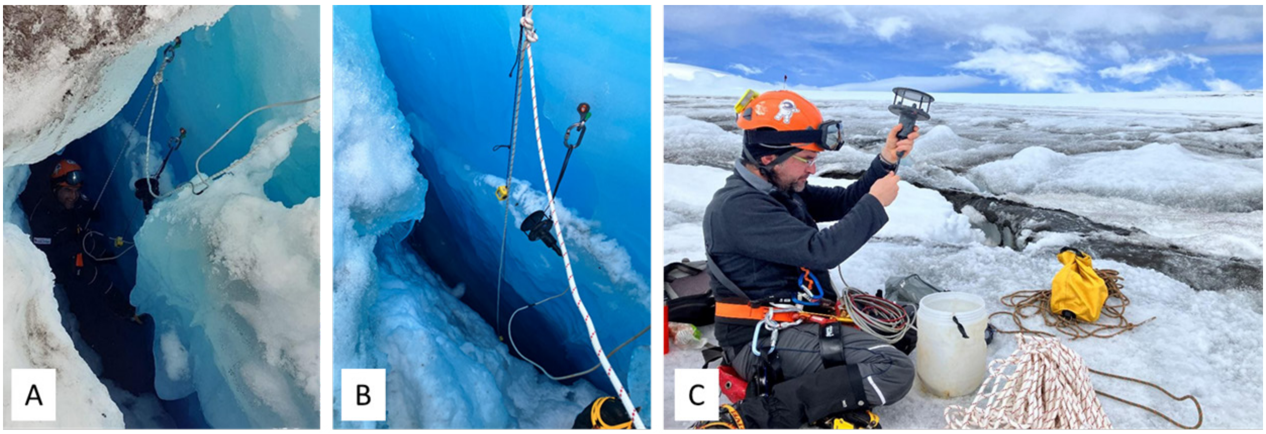

Figure 4. Preparation and position of anemometers. **A** and **B** installation process **C** surface check.

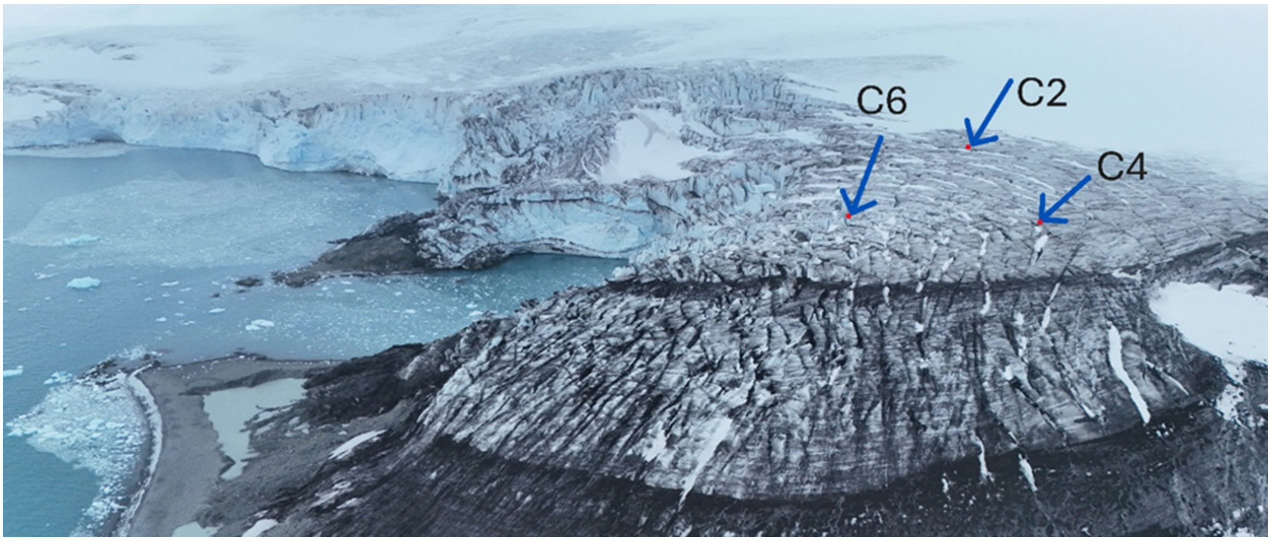

Figure 5. Crevasses with air flow measurements on the Balkan Ice Field.

2.2.4. Water temperature

For the measurements of water temperatures, we use the TG-4100 temperature data loggers. It is designed for extended underwater use at depths reaching 500 m. It records temperatures ranging from -40°C to +70°C. Housed in a durable, high-visibility yellow casing, it features a secure mounting point for stable placement. This device is particularly well-suited for applications such as monitoring in fisheries, rivers, and marine environments.

2.2.5. Solar activity, clouds and cosmic rays

A key feature of solar activity is the Sun's radio wave emissions at a wavelength of 10.7 cm (or a frequency of 2.8 GHz). This particular radio flux, commonly referred to as the 10.7 cm solar flux, has been a crucial tool for tracking solar radio emissions since 1946. Today, it is monitored by the Dominion Radio Astrophysical Observatory in Penticton, Canada (Tapping and Charrois 1994). It's an important measure of solar activity because it closely reflects changes in the solar ultraviolet output, which affects Earth's upper atmosphere and ionosphere.

Our solar activity data comes from the monthly bulletin of the Royal Observatory of Belgium (SILSO 2024). Between 29th of December 2024, and 15th of February 2025, multiple solar flares were recorded. The resulting coronal mass ejections (CMEs) were examined and modeled, showing a potential Earth impact. If the CME interacts more directly or strongly with Earth's magnetic field, more intense storm levels are possible. That said, the precise influence of solar storms on Earth's weather and climate is still not fully understood. It's a complex issue under active investigation, as many different factors shape Earth's weather patterns. While solar activity may contribute, it's just one piece of the puzzle.

In recent years, it has been discovered that there is a link between Earth's cloud cover, as seen from satellites, and galactic cosmic rays (GCR) (Svensmark and Friis-Christensen 1997) (fig. 6). Clouds affect the overall radiative balance of the atmosphere in two opposing ways: they cool the planet by reflecting incoming shortwave solar radiation, and they warm it by trapping outgoing longwave radiation emitted from the Earth's surface. Whether a cloud has a net warming or cooling effect depends mainly on how high it is and how thick it appears optically. Thin, high-altitude clouds usually contribute to warming, while thick, low-altitude clouds generally lead to cooling (Hartmann 1993). Estimates suggest that the global cloud cover currently causes a net cooling effect of about 17–35 W/m², highlighting the significant role clouds play in Earth's energy balance (Ohring and Clapp 1980; Ramanathan et al. 1989; Ardanuy et al. 1991). Therefore, if solar activity has any notable influence on cloud characteristics globally, it could have a major impact on Earth's climate (Svensmark and Friis-Christensen 1997; Svensmark et al. 1998).

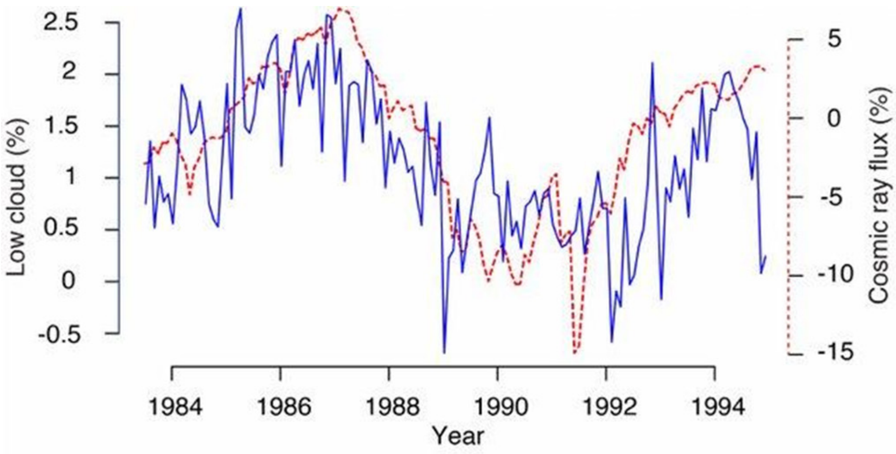

Figure 6. A reproduction of the Marsh and Svensmark (2000) correlation between low-level cloud cover (<3.2 km) from ISCCP (International Satellite Cloud Climatology Project, blue line), and the cosmic ray flux (red dashed line, values on right-hand axis) from the Climax Colorado and Moscow neutron monitor data (Čalogović and Laken 2015).

2.2.6. Antarctic climatic anomaly

The Bulgarian Antarctic base St. Kliment Ohridski, located on Livingston Island (62°38'S, 60°21'W) in the South Shetland Islands, lies approximately 60–70 km off the Antarctic Peninsula. This geographical position is of particular scientific importance, as the region is possible to be directly influenced by the Antarctic Climate Anomaly (ACA), a phenomenon in which East and West Antarctica often exhibit opposing temperature trends.

The Antarctic Climate Anomaly (Svensmark 2006) describes a unique climate response in Antarctica where cloud cover changes affect surface temperature in the opposite way compared to the rest of the world. Elsewhere on Earth, more clouds cause less sunlight, and that causes cooling. In Antarctica, more clouds trap infrared radiation, which causes warming.

During periods of increased solar activity, the flux of galactic cosmic rays (GCR) decreases, and this leads to reduced cloud cover. In Antarctica, fewer clouds lead to increased radiative heat loss, cooling of the surface and the air.

This response is most pronounced around 63° south latitude, where the so-called saddle point is located, the boundary at which the temperature response to small cloud cover changes sign (Fig. 7). Beyond this point, Antarctica becomes climatically isolated from the rest of the world.

Around −63° latitude (Fig. 7, dashed line), we observe a saddle point, the transition zone where the cloud-temperature response changes sign. North of this point, more clouds cause cooling. South of this point (Antarctica), more clouds cause warming (less clouds = cooling). This point corresponds to the Antarctic coastline and thus reflects the contrast in surface albedo between the continental landmass and the surrounding ocean.

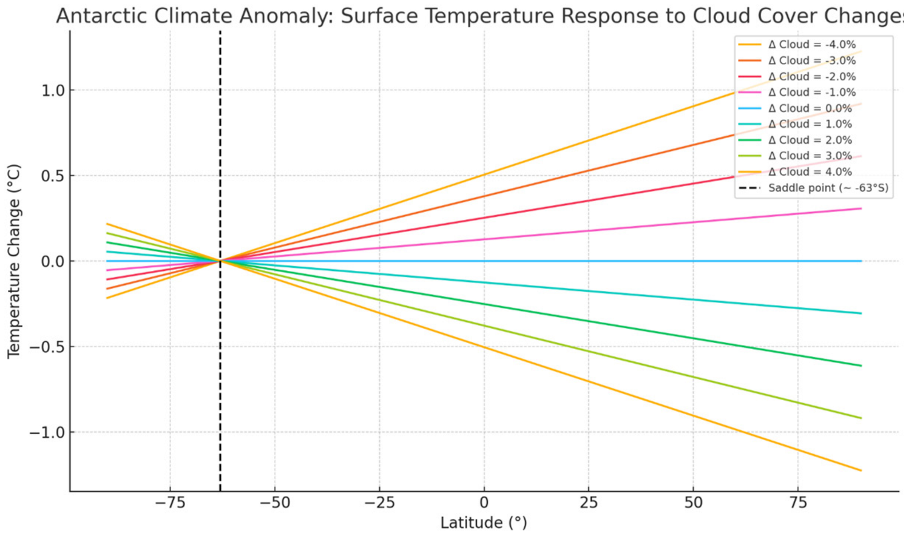

Figure 7. Surface temperature changes across latitudes when cloud cover is increased or decreased.

2.3. Data analysis

To process the temperature readings from each sensor placed within the glacier crevasses, we aggregated the measurements by calculating hourly averages. For instance, all data recorded between 11:00:00 and 11:59:59 on a given day were averaged to represent the value for the 11th hour. Since the sensors recorded data every 30 minutes, this typically meant averaging two values.

We applied the same method to the external environmental data and the data from the anemometer. In the case of the anemometer, we generally averaged around 60 readings per hour (or fewer if data were missing). When processing the air flow data, for each day, we summed all the speeds classified as 'Up' and all the speeds classified as 'Down'. We have the total amount of air that moved upward and the total amount that moved downward for each day. We also have the difference between the two. This resulted in one hourly data point per parameter—including crevasse temperatures, external conditions, and wind speed and direction. This approach allowed us to explore correlations between different types of data. To assess the consistency of the temperature readings, we calculated the variance for each sensor. In statistical terms, variance measures the average squared deviation from the mean, giving an indication of how much the readings fluctuate over time.

For a deeper analysis of the dataset, we applied Pearson correlation using SPSS statistical software. This enabled us to identify relationships between temperatures at various depths within the crevasses and external meteorological conditions and solar activity. To further investigate how deeply heat penetrates from the surface, we computed the statistical variance using a custom-written procedure in the Python programming language.

Because our primary goal was exploratory, we used standard Pearson correlations to quantify linear relationships between sunspot number, external meteorological variables and internal crevasse temperatures and airflow. These analyses treat hourly values as independent observations and do not explicitly model temporal autocorrelation within the time series. Likewise, we did not apply formal corrections for multiple testing across the different sites, depths and parameters, and we did not construct multivariate models that would control for additional potentially important drivers (e.g. synoptic-scale weather patterns, cloud cover, local wind regimes). As a consequence, the reported p-values should be regarded as approximate and indicative rather than strict tests of statistical significance, and our interpretation focuses on the sign, relative magnitude and spatial consistency of the correlations rather than on individual threshold exceedances.

3. Results

3.1. Temperature gradient and depth of heat penetration from the surface

3.1.1. Contell Glacier

Fig. 8 is a schematic diagram showing a map of the crevasse with the sensors placed inside the central part of the Contell Glacier. During the period from January 6, 2025, to February 4, 2025, the measurements indicated stability in relation to external dynamic temperature fluctuations and a stable zone of consistently negative temperatures. The temperature at a depth of 11 meters remained constant at −0.02°C. The glacier is being studied with sensors for the first time, so this measurement and the identification of the melt zone and the zone of sub-zero temperatures can be used as a starting point for future research.

Fig. 9 shows the recorded temperatures in the crevasses, along with the external temperature. It is evident how the variation of internal temperatures repeating decreases with depth, and the temperatures become more constant. The red line indicates external temperature for the period of three weeks, and the other line indicates internal temperatures through 3 m.

Table 1 shows the correlations between sunspots and each of the temperatures recorded by the sensors. Correlations with a P-value < 0.05 are statistically significant. These significant correlations are negative, meaning that higher sunspot numbers are associated with lower temperatures.

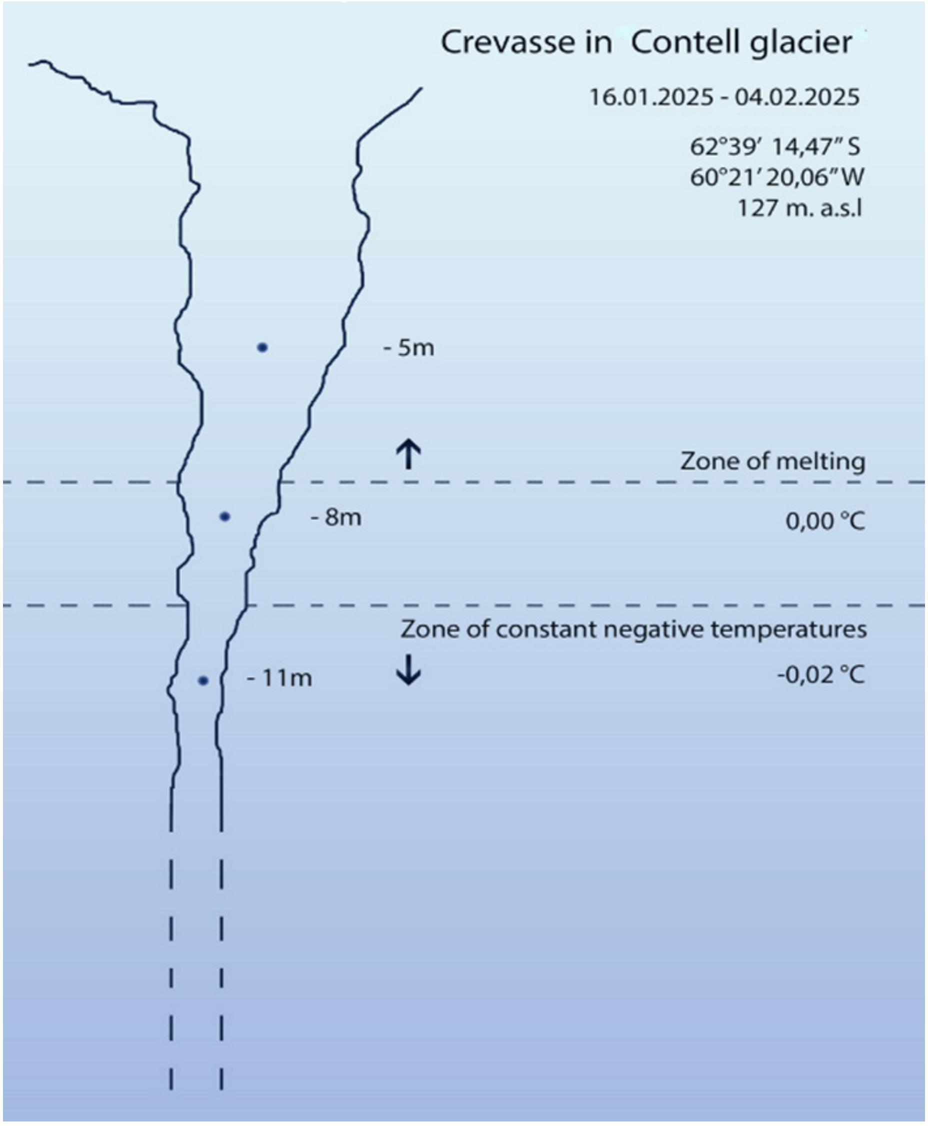

Figure 8. Distribution of sensors within the crevasse.

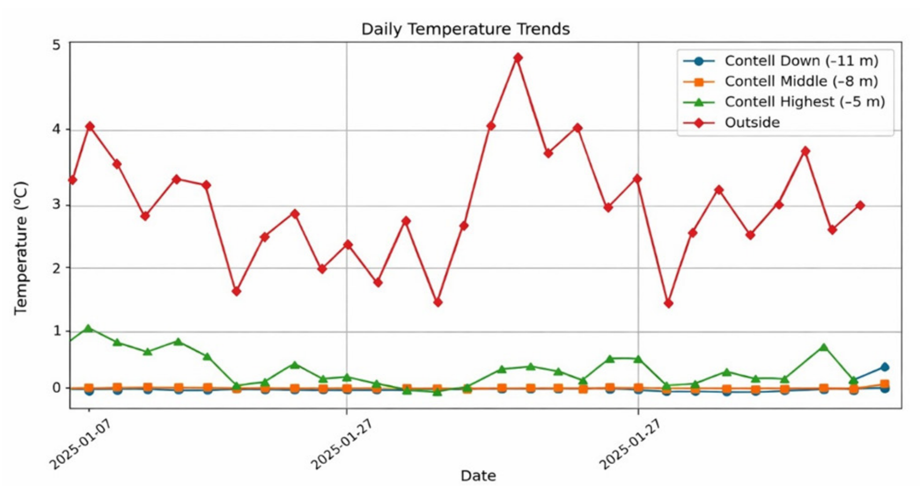

Figure 9. Visualization of the temperature gradient into the Contell crevasse.

Table 1. Correlation coefficients between sunspot activity and inside temperatures for the period from 06.01.2025 to 03.02.2025.

Independent variable	Number of cases	Correlation coefficient	P-value (Significance level)
Outside temperatures:	37	0.16	0.35
Temp. in Contell −5 m	28	−0.4	0.03
Temp. in Contell −8 m	28	−0.26	0.01
Temp. in Contell −11m	28	−0.3	0.13

3.1.2. Johnsons glacier

The Johnsons Glacier was studied for two crevasses: JD1 and JD2 (Fig. 10). JD1 is located near the glacier's front in the ablation zone, with coordinates (62°39'47.83"S and 60°21'45.71"W) and temperature and anemometer sensors were placed in it. The deepest sensor was at a depth of 15 meters. For the data from the anemometer, from 270° to 360° and from 0° to 90°, the direction is coded as "Down". From 90° to 270°, it is coded as "Up". In other words, the reference axis is assumed to point straight down. When the measured speed is very low—below 0.04 m/s—the direction is not recorded, and it's marked as "No". Thus, direction has three values: "Up", "Down", and "No". Then, for each day, we sum up all the airspeeds recorded for "Up" and for "Down". So, for each day, we have the total volume of air that moved upward, the total volume of air that moved downward and the difference (diff) between them.

The correlation analysis (Table 2) demonstrates a negative correlation, meaning that during periods of high solar activity, the difference is negative. This suggests that air masses have moved downward more intensely when solar activity increases.

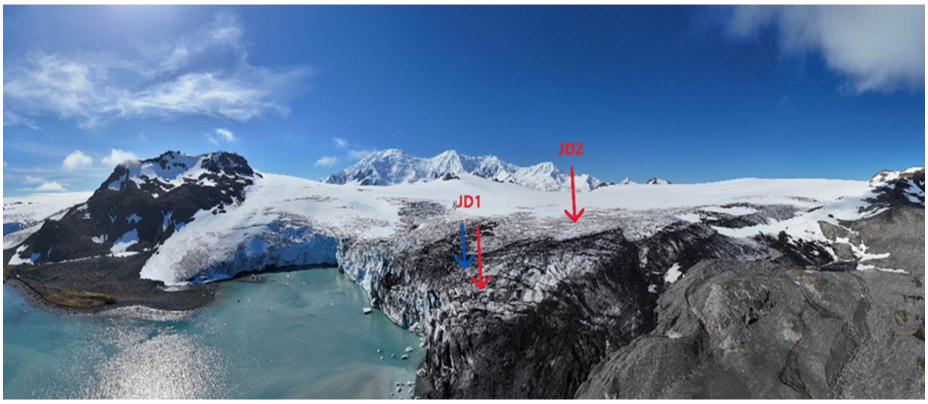

Figure 10. Position of the sensors in crevasses JD1 and JD2.

Table 2. Correlation coefficients between sunspot activity and the difference (diff).

Independent variable	Number of cases	Correlation coefficient	P-value (Significance level)
Sunspots	18	−0.23	0.36
Outside temperature	18	−0.14	0.59

JD2 is located at the boundary between the accumulation zone and the ablation zone with coordinates (62°39'53.09"S and 60°21'37.79"W). It had one sensor installed at a depth of 12 m, along with a rope to measure the distance between the walls of the crack.

From January 20 to January 25, 2025, a water temperature sensor was placed in the stream flowing from the glacier's periphery. It recorded a constant temperature of 0.05°C.

In crevasse GD1, an anemometer and three air temperature sensors were installed. The anemometer data, correlated with solar activity and external temperatures, are presented in Table 2. The sensors intended to detect the temperature gradient did not indicate a zone of sub-zero temperatures. This phenomenon is likely due to the crevasse's proximity to the glacier's terminus in the zone of fastest melting and movement, where there is no stability and the glacier is losing mass.

In crevasse GD2, from February 1 to February 10, 2025, an air temperature sensor was placed at a depth of 10 m. It showed a stable temperature around 0°C, suggesting it was located on the edge of the zone of constant sub-zero temperatures. This sensor's data was also correlated with solar activity and is presented in Table 3. Correlations are statistically significant. These significant correlations are negative, similar to Contell glacier, meaning that higher sunspot numbers are also like in Contell, associated with lower temperatures in the crevasse.

Table 3. Presenting the correlation between sunspot activity and temperatures in JD2. Measured from February 1 to February 10, 2025.

Independent variable	Number of cases	Correlation coefficient	P-value (Significance level)
Outside	37	0.16	0.35
JD2	9	-0.79	0.01

3.1.3. Balkan Ice Field

In the Balkan Ice Field, following field investigations started on 29th of December 2024, it was established that only four crevasses (C3, C2, C4, C5) and one subglacial cave (C1) at the edge of the ablation zone (Fig. 11) were open and suitable for the installation of measuring equipment. These features are located on the boundary between the accumulation zone and the ablation zone, with the main crevasse crossing the glacier up to its middle section.

By using alpine techniques to descend into the crevasses, it was observed that their depths were comparable to the glacier's thickness, which is around 100 m in this area (the entrance zone is situated at 102 m a.s.l.). Description of sensor placement locations:

- C1—cave located at the contact point between the glacier ice and its bedrock. We used the cave to conduct measurements of the subglacial water temperature and the air temperature.
- C2—this crevasse was enormous and deep. Unfortunately, we only had measurements from it for 48 hours before the snow cover collapsed along with part of the wall, sweeping away five of our sensors. The reached depth for the deeper sensor was 25 m.

- C3—temporary place for one anemometer sensor for three days.
- C4—air temperature sensors and anemometer for the period of 20 days, at a depth of 13 m.
- C5—air temperature sensor at a depth of 10 m.
- C7—a sensor used to measure the temperature of meltwater exiting at the glacier's periphery.
- C6—deep crevasse with sensors for air temperature at a depth of 21 m and an anemometer.

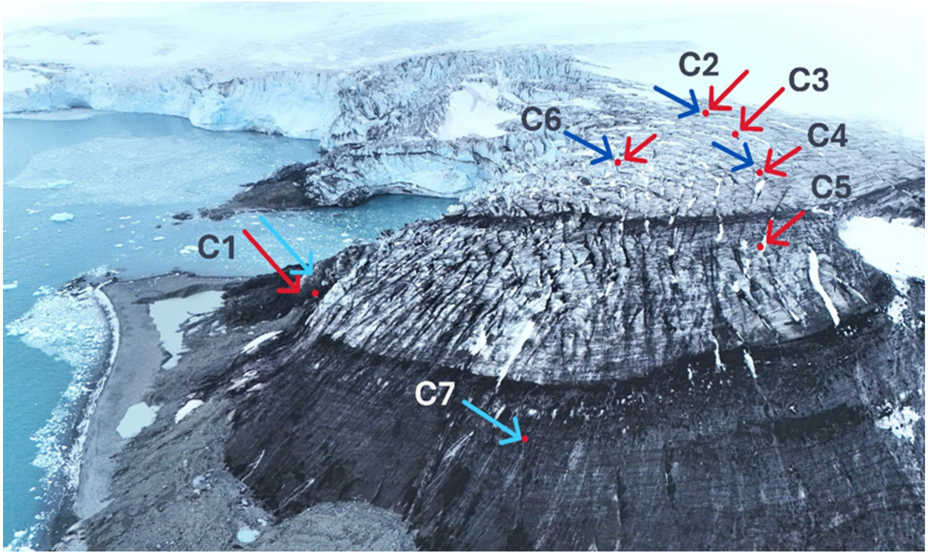

Figure 11. Sensor placement locations. Red arrows show the position of air-temperature sensors, and light-blue arrows in C7 and C1 are sensors for sub-glacier water temperature.

The Balkan Ice Field is of particular interest because it was the main research site one year earlier, during the 32nd Bulgarian Antarctic expedition (Parov 2024). It was precisely there that the zone of consistently negative temperatures and the negative correlation with solar activity were first identified. This also marked the beginning of investigations into the direction and intensity of the airflows circulating within the crevasses.

Over the course of that year, under conditions of increasing solar activity due to the approach of the solar maximum in the 11-year cycle, we observed a clear expansion of the glacier's ablation zone with approximately 50 m, a downward shift of 10 m in the stable zone of permanently negative temperatures, and a 2- to 3-fold widening of the crevasses in previously studied sections of the glacier. In three of the studied crevasses, we encountered lakes at their bottom, a phenomenon that had not been observed during the previous year.

3.1.3.1. Results for cave C1

The cave was located at the front of the glacier (62°38'03.21"S, 60°20'16.42"W), providing quick access to the contact zone between the bedrock and the ice. The approximate dimensions of the gallery were about 1 m in width and 2 m in height. After the 10th meter in length, the shape of the gallery changed to a "tunnel oven" type, with a height of about 50 cm, following the flow of the subglacial river.

We installed a water temperature sensor, which recorded a stable, constant temperature of 0.03°C, and an air temperature sensor. The air temperature remained around 0.1°C with minor fluctuations.

The period of 15th of January 2025, to 19th of January 2025, is too short for significant research, but the cave entrance was very dangerous due to the fast melting of the ice. Nevertheless, we have five days of data, which is sufficient to establish a correlation between temperature and solar activity. Although weak, the correlation is negative, consistent with observations from other glaciers (Table 4).

Table 4. Presenting the correlation between sunspots and temperatures in the cave.

Independent variable	Number of cases	Correlation coefficient	P-value (Significance level)
The cave temperature	5	−0.39	0.52

3.1.3.2. Results for crevasse C2

The location of the placement point is 62°38'12.52"S and 60°20'03.16"W, 107 m a.s.l. (Fig. 12). Unfortunately, due to the collapse of the ceiling and part of the crevasse walls, we lost five of our sensors 26 hours after the measurements began. The lowest sensor was positioned at a depth of −21 m. The data showed a stable temperature of 0°C from the 15th meter downward. Interestingly, at the geographic coordinates of this crevasse, we measured an average width of 1.8–2 meters the previous year, whereas this year the width reached up to 6 m. We used the software of the Drone DJI Phantom 4 Pro to establish the dimensions of the crevasse (Fig. 13).

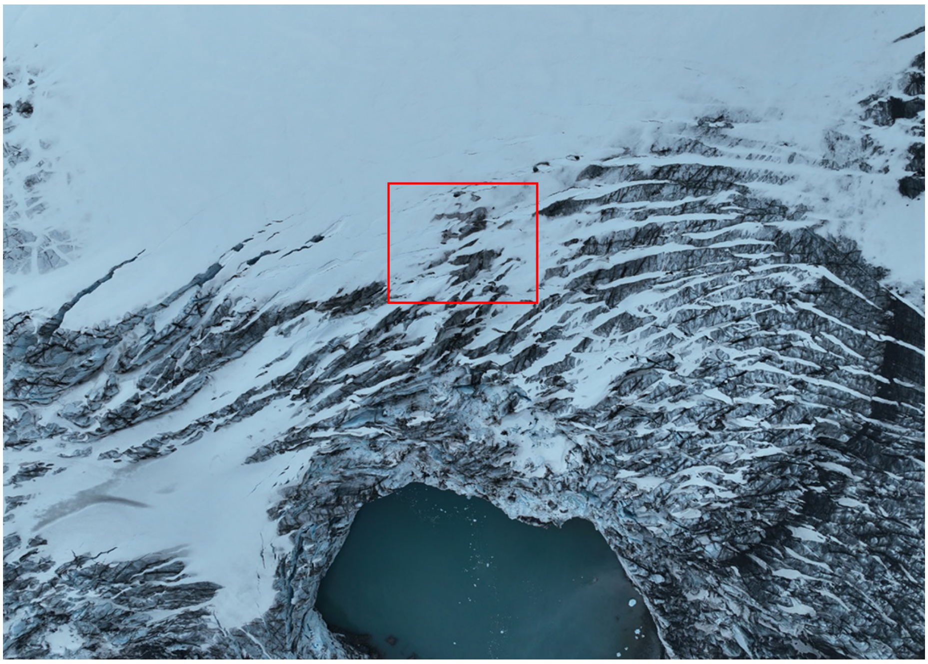

Figure 12. Position of the sensors in C2 (red square).

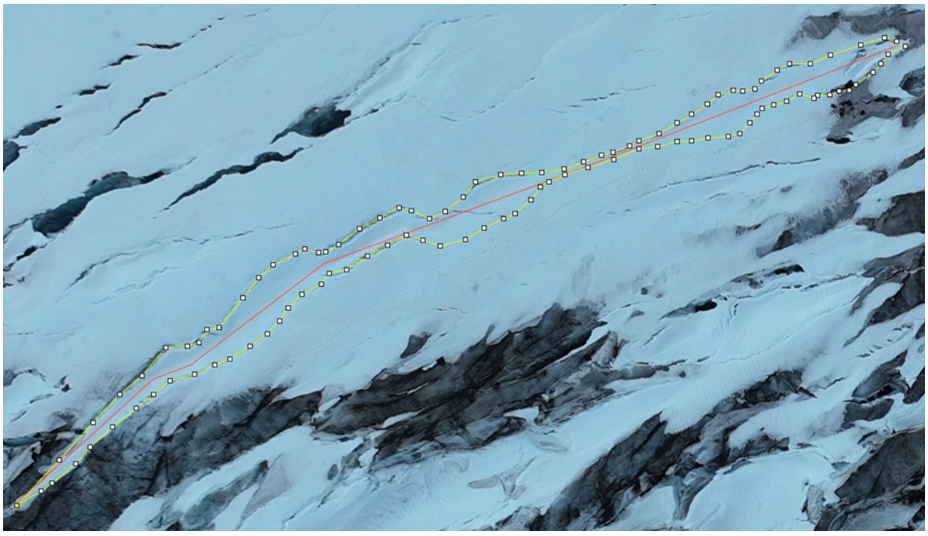

Figure 13. Determination of crevasse lid area.

We conducted measurements and used the drone's software to determine both the area of the crevasse lid and its average width. This allowed us to calculate that, over the course of one year, the crevasses in the study area had expanded. In the previous year, at the same coordinate zone, the maximum crevasse width was 2 m, whereas it now averages 5 m. The total area is 878.845 m^2. The total crack length is 130.4 m, which gives a mean width of 6.74 m; line length: 29px; resolution: 0.18706m/px; crack width: 5.425 m, and error of 0.200 m.

3.1.3.3. Results for crevasse C3

An anemometer was deployed within this crevasse for a period of one week. The graphical analysis of the data indicates a potential correlation between the downward movement (red line) of air masses and increased sunspot activity (Fig. 14). A deviation observed at the beginning of the graph may be attributed to a strong geomagnetic storm, likely triggered by an X-class solar flare recorded on January 4, 2025.

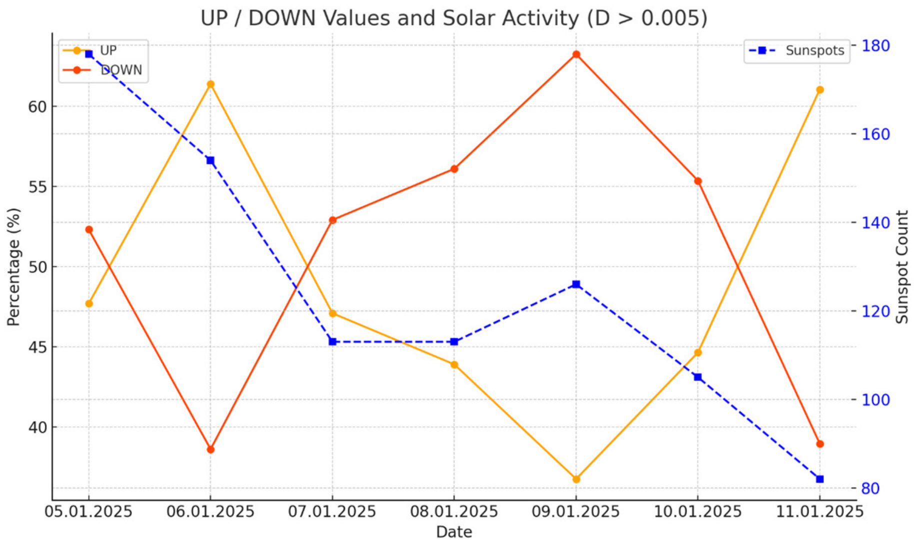

Figure 14. Air movement in relation to increased solar activity.

3.1.3.4. Results for crevasse C4

The position of sensors is (62°38'12.19"S, 60°20'15.67"W). Table 5 shows the correlation between solar activity and the difference in the amount of air moving upward or downward in the cracks. To calculate the difference, for each day we subtracted the amount of air moving downward from the total amount moving upward. It can be seen that there is a negative correlation. This means that during periods of high solar activity, the difference (diff) tends to be negative—in other words, more air has moved downward. We also observe a relationship between the increase in solar activity and the downward movement of air masses (Fig. 15).

The negative correlation between sunspot variability and the amount of air moving upward and downward within the crevasse indicates that the air above the glacier cools during periods of increased solar activity and subsequently “sinks” into the crevasses.

Table 5. Presenting the correlation between sunspots and the difference in the amount of air moving upward and downward in the crevasse C4.

Independent variable	Number of cases	Correlation coefficient	P-value (Significance level)
Sunspots	19	-0.51	0.03
Outside Temperature	19	-0.1	0.68

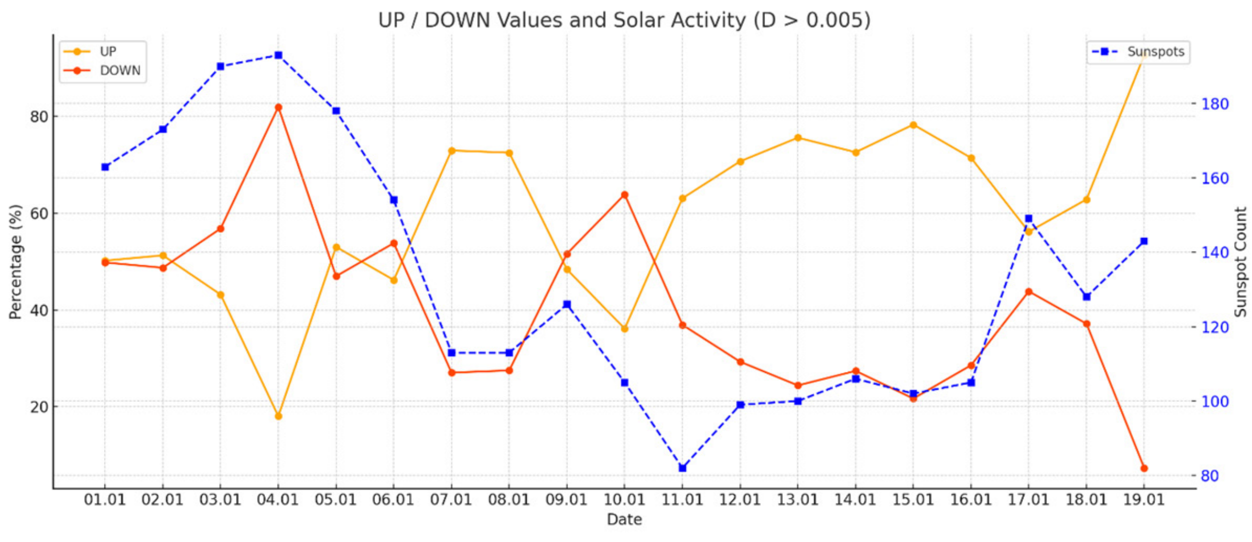

Figure 15. Relation between the downward movement (red line) of air masses and increased sunspot activity.

3.1.3.5. Results for crevasse C5

The location of the sensors on the glacier is 62°38'12.04"S, 60°20'17.71"W. We used this peripheral crevasse to compare the change in average temperatures at a depth of 10 m with measurements taken 10 months earlier at the same location. During the 2024 expedition, the average temperature at a depth of 10 m was −0.0182°C, whereas the current calculation shows 0.0163°C.

3.1.3.6. Results for crevasse C6

The location of the sensors is 62°38'10.89"S, 60°20'11.77"W. The crevasse C6 is located near the edge of the glacier (Fig. 16). We observed many ice stalactites inside. The reached depth was 30 m, with a sensor placed at a depth of 22 m. At a depth of 22 m, the measured temperature was a constant −0.02°C. This temperature, compared to measurements in the same area 10 months earlier, is the same, but this zone of consistently negative temperatures has sunk 10 m deeper.

Figure 16. Inside the crevasse C6.

3.1.3.7. Results for the outside waters C7

In January 2025, temperature data were collected from four distinct locations: two air data loggers positioned at different elevations—one below the Bulgarian Antarctic base at "Kutsoto Kuche" and another at the upper part of Contell Glacier—as well as two sensors measuring the temperature of water emerging from glacial sources, Water Temp, monitoring outflow from the periphery of Balkan Ice Field, and Water JD Temp, placed at the outlet of the Johnsons Glacier. The aim of the study is to analyze the thermal behavior of air versus water and to investigate potential correlations between them.

The average temperature of the water flowing from the periphery of the Balkan Ice Field was measured at 0.113°C over a period of 12 days, from January 2, 2025, to January 14, 2025. In the outlet water flow of Johnsons Glacier, we put the sensor for water temperature for six days, from the 20th of January 2025, to the 25th of January 2025. The average temperature there is 0.062°C.

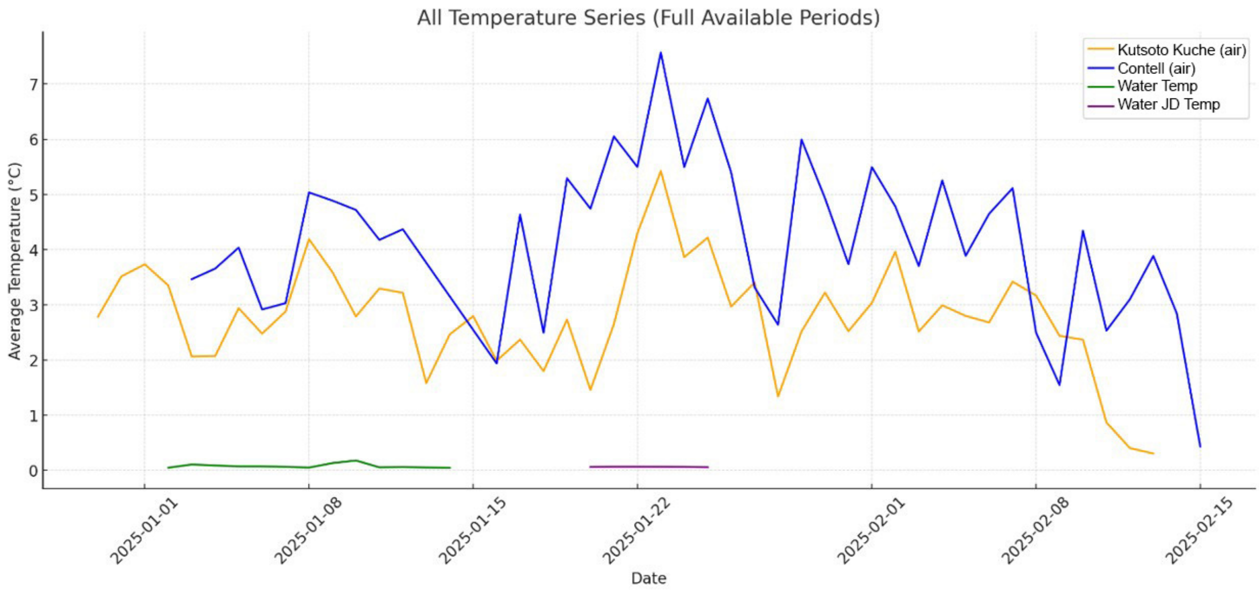

Figure 17. Comparison between two external temperature sensors, and below, the two sensors measuring the temperature of the outflowing water can be seen.

Fig. 17 shows a comparison between surface temperature sensors (Kutsoto Kuche and Contel) and those submerged in glacial meltwater (Water Temp and JD Temp). It appears that only the green line, representing the outflow from the Balkan Ice Field, exhibits a weak response to external air temperatures. The JD series covers only a few days and is therefore presented for informational purposes only.

An interesting contrast emerges between sea-level air temperatures recorded by the Kutsoto Kuche sensor, which was positioned in shade and sheltered from wind, and the Contell sensor (blue line), which was placed inside a rock crevice approximately 250 m. a.s.l. on Charrua Ridge. The pronounced thermal inertia of the surrounding rock, which absorbs and stores solar radiation, appears to result in artificially elevated temperature readings at higher elevations.

4. Discussion

The analysis of these results will help us in the investigation of the Antarctic climate anomaly located around 63°S latitude in the peripheral zones of Antarctica. The present study provides new empirical evidence supporting the hypothesis that solar activity influences subsurface glacial temperature dynamics in Antarctica, particularly within crevasse-drainage systems located near the glacier surface. The observed negative correlation between sunspot number and internal air temperatures in all studied sites—Balkan Ice Field, Contell Glacier, and Johnsons Glacier—suggests that this relationship is not incidental but may represent a broader climatic mechanism at work in polar environments. These findings align with the concept of the Antarctic Climate Anomaly from (Svensmark and Friis-Christensen 1997), whereby increased solar activity through its modulation of galactic cosmic rays (GCRs) and consequent cloud formation leads to a cooling effect over Antarctica, in contrast to warming observed elsewhere on the planet. The mechanism likely involves decreased cloud cover during periods of heightened solar magnetic activity, resulting in reduced longwave back-radiation and enhanced radiative cooling over the high-albedo Antarctic ice surface. This contrasts with lower-latitude regions, where clouds predominantly cool by reflecting incoming solar radiation. The findings of Svensmark and Friis-Christensen (1997) and the corresponding results were criticized as entirely incorrect by Jørgensen and Hansen (2000). The comment dates back to 1997, and since then, a significant accomplishment has been made. Experimental results have shown that ions induce the nucleation of aerosols (Svensmark et al. 2007; Kirkby et al. 2011). In addition, it has been demonstrated that ions accelerate the growth of aerosols (Svensmark et al. 2017). Faster growth increases the likelihood that aerosols will survive to become cloud condensation nuclei. From observations of Forbush decreases (sudden drops in cosmic ray flux lasting about a week), changes have been observed in several cloud parameters, including cloud fraction, cloud optical thickness, liquid water path, and effective cloud droplet size (Svensmark et al. 2009). Data from the CERES instrument also reveals the impact on the Earth's radiative budget (Svensmark et al. 2021).

In the studied crevasses, this radiative mechanism appears to translate into increased downward airflows, enhanced vertical convection, and reduced internal air temperatures. The deeper crevasses (C2 and C6 in the Balkan Ice Field, and JD2 in Johnsons Glacier) demonstrate stronger negative thermal responses during periods of elevated solar activity. This supports the idea that solar-driven atmospheric changes penetrate into vertical glacial structures, influencing microclimates at depths exceeding 20 meters. Furthermore, the emergence of subglacial water bodies, along with the measurable expansion of crevasses and the lowering of the permanently sub-zero isotherm by up to 10 meters, indicate that climate-induced mass loss is accelerating in the ablation zones of peripheral Antarctic glaciers. The Contell Glacier, in contrast, exhibited a more stable temperature profile and a shallower negative temperature zone, potentially due to its alpine morphology and topographic shielding, characteristics that may confer greater resistance to external climate forcing.

The short-term but significant temperature response measured inside a subglacial cave further supports the hypothesis. Despite the limited five-day measurement period, the negative correlation between solar activity and cave air temperature mirrors patterns observed elsewhere, suggesting that the effect is consistent even in confined subglacial environments.

Nevertheless, as is widely recognized, correlation does not imply causation. It remains essential to delineate the precise microphysical pathways through which cosmic rays may influence cloud formation, particularly in high-latitude contexts where radiative feedbacks deviate sharply from the global average.

Overall, these results emphasize the necessity of incorporating solar-terrestrial interactions, especially those related to cosmic ray flux and cloud microphysics, into regional climate models for Antarctica. Understanding how global solar variability translates into local thermodynamic changes within glacier systems is crucial for accurately forecasting ice mass balance trends, meltwater contributions, and glacier stability under future climate conditions.

5. Conclusions

In accordance with the research objectives, the main conclusions concern vertical temperature structure, airflow patterns, spatial and temporal variability, solar activity and internal temperatures, subglacial access and sediment sampling, mechanism and complexity of the solar signal. For vertical temperature structure, all monitored crevasses in the Contell, Johnsons, and Balkan Glaciers exhibit a clear vertical temperature gradient, with decreasing temperature and damped variability with depth. Below 9–11 m, the variance approaches zero, and a quasi-constant temperature of about (−0.02 °C) is reached, which we interpret as the penetration depth of surface thermal forcing in these crevasse and drainage systems. Concerning airflow patterns, ultrasonic anemometers reveal highly variable airflow with a pronounced diurnal cycle: weaker motions around local noon and stronger flows near midnight. Upward flows intensify during storms, precipitation or strong surface winds, whereas downward flows dominate under calm conditions, with distinct post-midnight speed peaks. Spatial and temporal variability show on annual time scales that both spatial and temporal variability are evident. In marginal crevasses, the constant-temperature zone can migrate upward under persistent strong winds, whereas in central crevasses it remains deeper and more stable. At Balkan Ice Field, this zone deepened by about 6–10 m relative to the previous year, while Contell and Johnsons Glaciers showed greater thermal stability, underscoring the key role of wind.

The monitored solar activity and internal temperatures in crevasses show predominantly negative correlations between internal temperatures and indices of solar activity, some of which reach nominal statistical significance. This indicates a measurable but moderate solar, meteorological influence that varies with crevasse type. Concerning subglacial access and sediment sampling, fieldwork documented successful access to subglacial cavities beneath the Balkan Ice Field, allowing sediment sampling in zones with stable air temperatures above flowing water and enhanced surface melt. Although peripheral to the main focus of this thesis, these samples provide useful material for future interdisciplinary studies. Overall, about the mechanism and complexity of the solar signal, the analyses support statistically significant, robust negative relationships between internal temperatures in some crevasses and sunspot numbers. The effect is likely indirect and mediated by changes in cloudiness, atmospheric circulation, humidity and local weather, implying a complex, not always linear response that depends on local morphological and meteorological conditions.

A key limitation of this study is the simplicity of statistical treatment. The temperature, airflow and solar activity records are strongly autocorrelated in time, yet we analyse them using simple Pearson correlations that assume independence between successive observations. In addition, a relatively large number of pairwise correlations were computed for different sensors, depths and sites without applying formal corrections for multiple testing, and the short length of the time series, together with limited ancillary data, prevented us from building multivariate models that would control other relevant atmospheric and oceanic drivers. Taken together, these factors imply that the nominal p-values may overstate the strength of the statistical evidence, and individual correlations, especially those close to the 0.05 threshold, should be interpreted with caution. Our conclusions, therefore, rely primarily on the robustness of the negative relationship between solar activity and internal glacier temperatures across independent sites and depths, and on the physical plausibility of the proposed mechanism, rather than on any single statistical test.

These findings underscore the importance of integrated climatological and glaciological monitoring to resolve complex cryosphere-atmosphere interactions. Furthermore, they lend empirical support to theoretical models proposing that GCR-induced ionization influences cloud microphysics, thereby modulating regional energy balances. Further research into these microphysical processes is critical to improving climate models for polar regions, particularly under scenarios of increasing solar variability.

The Antarctic response to solar forcing appears unique, nonlinear, and regionally modulated, reinforcing the urgency of polar-specific climate modeling and deeper exploration of the relation between solar activity, cosmic rays, clouds, and the climate nexus.

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Additional information

Conflict of interest

No conflict of interest was declared.

Ethical statement

No ethical statement was reported.

Use of AI

No use of AI was reported.

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Author contributions

The author solely contributed to this work.

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Data availability

All of the data that support the findings of this study are available in the main text or Supplementary Information.